Department of Energy
Fundamentals Handbook

INSTRUMENTATION AND CONTROL
Module 4
Flow Detectors

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NONE

REFERENCES

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TERMINAL OBJECTIVE

1.0 Given a flow instrument, **RELATE** the associated fundamental principles, including possible failure modes, to that instrument.

ENABLING OBJECTIVES

1.1 **EXPLAIN** the theory of operation of a basic head flow meter.

1.2 **DESCRIBE** the basic construction of the following types of head flow detectors:
- a. Orifice plates
- b. Venturi tube
- c. Dall flow tube
- d. Pitot tube

1.3 **DESCRIBE** the following types of mechanical flow detectors, including the basic construction and theory of operation.
- a. Rotameter
- b. Nutating Disk

1.4 **DESCRIBE** density compensation of a steam flow instrument to include the reason density compensation is required and the parameters used.

1.5 Given a block diagram of a typical flow detection device, **STATE** the purpose of the following blocks:
- a. Differential pressure (ΔP) transmitter
- b. Extractor
- c. Indicator

1.6 **STATE** the three environmental concerns which can affect the accuracy and reliability of flow sensing instrumentation.

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HEAD FLOW METERS

Flow measurement is an important process measurement to be considered in operating a facility's fluid systems. For efficient and economic operation of these fluid systems, flow measurement is necessary.

EO 1.1 EXPLAIN the theory of operation of a basic head flow meter.

EO 1.2 DESCRIBE the basic construction of the following types of head flow detectors:
- **a. Orifice plates**
- **b. Venturi tube**
- **c. Dall flow tube**
- **d. Pitot tube**

Head flow meters operate on the principle of placing a restriction in the line to cause a differential pressure head. The differential pressure, which is caused by the head, is measured and converted to a flow measurement. Industrial applications of head flow meters incorporate a pneumatic or electrical transmitting system for remote readout of flow rate. Generally, the indicating instrument extracts the square root of the differential pressure and displays the flow rate on a linear indicator.

There are two elements in a head flow meter; the primary element is the restriction in the line, and the secondary element is the differential pressure measuring device. Figure 1 shows the basic operating characteristics of a head flow meter.

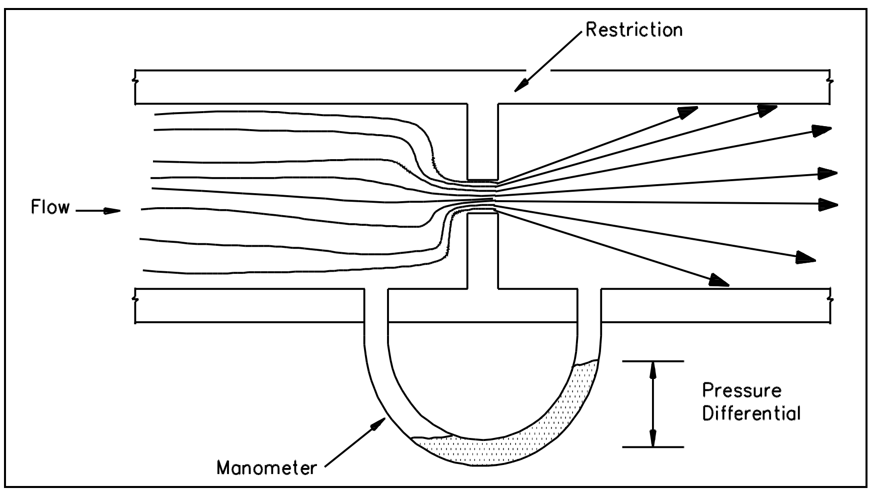

Figure 1 Head Flow Meter

The flowpath restriction, such as an orifice, causes a differential pressure across the orifice. This pressure differential is measured by a mercury manometer or a differential pressure detector. From this measurement, flow rate is determined from known physical laws.

The head flow meter actually measures volume flow rate rather than mass flow rate. Mass flow rate is easily calculated or computed from volumetric flow rate by knowing or sensing temperature and/or pressure. Temperature and pressure affect the density of the fluid and, therefore, the mass of fluid flowing past a certain point. If the volumetric flow rate signal is compensated for changes in temperature and/or pressure, a true mass flow rate signal can be obtained. In Thermodynamics it is described that temperature and density are inversely proportional, while pressure and density are directly proportional. To show the relationship between temperature or pressure, the mass flow rate equation is often written as either Equation 4-1 or 4-2.

$$\dot{m} = KA\sqrt{\Delta P(P)} \tag{4-1}$$

$$\dot{m} = KA\sqrt{\Delta P(1/T)} \tag{4-2}$$

where

$\dot{m}$ = mass flow rate (lbm/sec)
A = area (ft^2)
ΔP = differential pressure (lbf/ft^2)
P = pressure (lbf/ft^2)
T = temperature (°F)
K = flow coefficient

The flow coefficient is constant for the system based mainly on the construction characteristics of the pipe and type of fluid flowing through the pipe. The flow coefficient in each equation contains the appropriate units to balance the equation and provide the proper units for the resulting mass flow rate. The area of the pipe and differential pressure are used to calculate volumetric flow rate. As stated above, this volumetric flow rate is converted to mass flow rate by compensating for system temperature or pressure.

Orifice Plate

The orifice plate is the simplest of the flowpath restrictions used in flow detection, as well as the most economical. Orifice plates are flat plates 1/16 to 1/4 inch thick. They are normally mounted between a pair of flanges and are installed in a straight run of smooth pipe to avoid disturbance of flow patterns from fittings and valves.

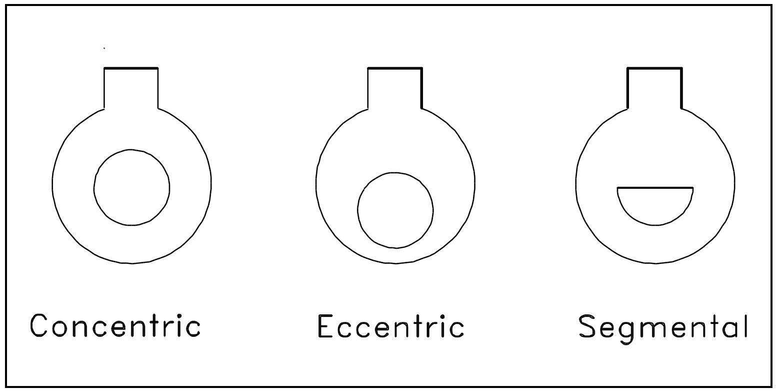

Figure 2 Orifice Plates

Three kinds of orifice plates are used: concentric, eccentric, and segmental (as shown in Figure 2).

The concentric orifice plate is the most common of the three types. As shown, the orifice is equidistant (concentric) to the inside diameter of the pipe. Flow through a sharp-edged orifice plate is characterized by a change in velocity. As the fluid passes through the orifice, the fluid converges, and the velocity of the fluid increases to a maximum value. At this point, the pressure is at a minimum value. As the fluid diverges to fill the entire pipe area, the velocity decreases back to the original value. The pressure increases to about 60% to 80% of the original input value. The pressure loss is irrecoverable; therefore, the output pressure will always be less than the input pressure. The pressures on both sides of the orifice are measured, resulting in a differential pressure which is proportional to the flow rate.

Segmental and eccentric orifice plates are functionally identical to the concentric orifice. The circular section of the segmental orifice is concentric with the pipe. The segmental portion of the orifice eliminates damming of foreign materials on the upstream side of the orifice when mounted in a horizontal pipe. Depending on the type of fluid, the segmental section is placed on either the top or bottom of the horizontal pipe to increase the accuracy of the measurement.

Eccentric orifice plates shift the edge of the orifice to the inside of the pipe wall. This design also prevents upstream damming and is used in the same way as the segmental orifice plate.

Orifice plates have two distinct disadvantages; they cause a high permanent pressure drop (outlet pressure will be 60% to 80% of inlet pressure), and they are subject to erosion, which will eventually cause inaccuracies in the measured differential pressure.

Venturi Tube

The venturi tube, illustrated in Figure 3, is the most accurate flow-sensing element when properly calibrated. The venturi tube has a converging conical inlet, a cylindrical throat, and a diverging recovery cone. It has no projections into the fluid, no sharp corners, and no sudden changes in contour.

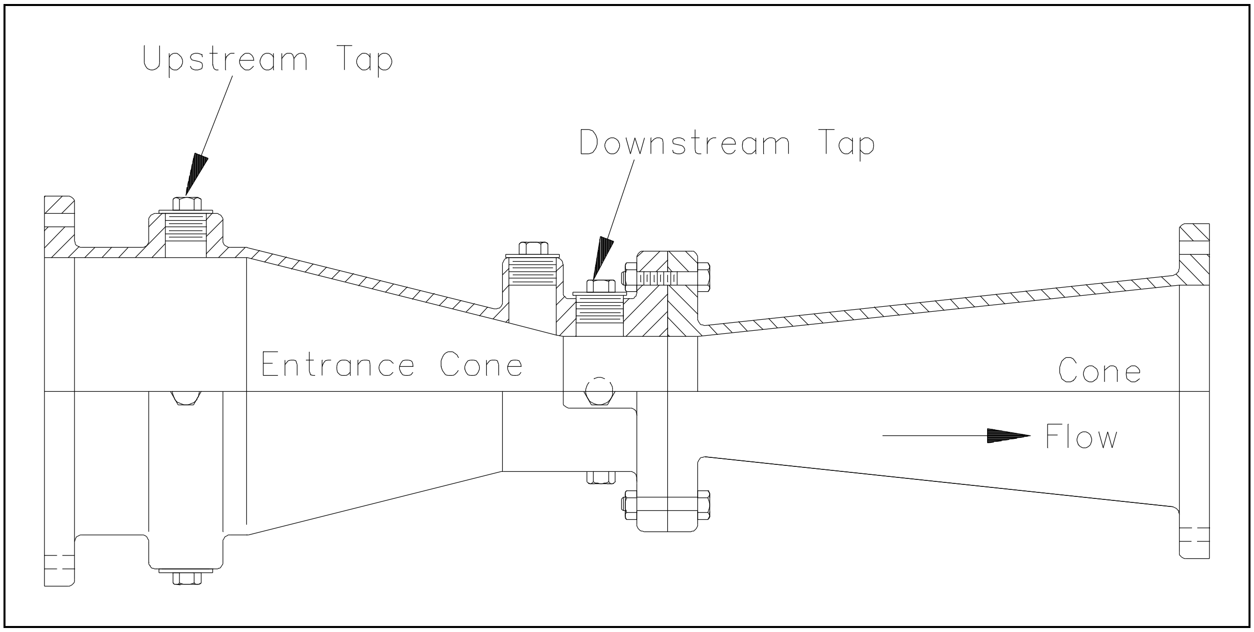

Figure 3 Venturi Tube

The inlet section decreases the area of the fluid stream, causing the velocity to increase and the pressure to decrease. The low pressure is measured in the center of the cylindrical throat since the pressure will be at its lowest value, and neither the pressure nor the velocity is changing. The recovery cone allows for the recovery of pressure such that total pressure loss is only 10% to 25%. The high pressure is measured upstream of the entrance cone. The major disadvantages of this type of flow detection are the high initial costs for installation and difficulty in installation and inspection.

Dall Flow Tube

The dall flow tube, illustrated in Figure 4, has a higher ratio of pressure developed to pressure lost than the venturi flow tube. It is more compact and is commonly used in large flow applications. The tube consists of a short, straight inlet section followed by an abrupt decrease in the inside diameter of the tube. This section, called the inlet shoulder, is followed by the converging inlet cone and a diverging exit cone. The two cones are separated by a slot or gap between the two cones. The low pressure is measured at the slotted throat (area between the two cones). The high pressure is measured at the upstream edge of the inlet shoulder.

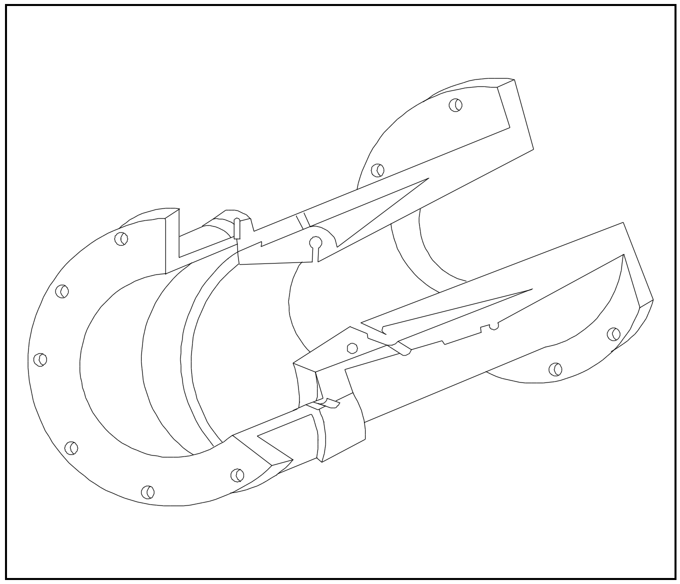

Figure 4 Dall Flow Tube

The dall flow tube is available in medium to very large sizes. In the large sizes, the cost is normally less than that of a venturi flow tube. This type of flow tube has a pressure loss of about 5%. Flow rate and pressure drop are related as shown in Equation 4-3.

$$\dot{V} = K\sqrt{\Delta P} \tag{4-3}$$

where

$\dot{V}$ = volumetric flow rate
K = constant derived from the mechanical parameters of the primary elements
ΔP = differential pressure

Pitot Tube

The pitot tube, illustrated in Figure 5, is another primary flow element used to produce a differential pressure for flow detection. In its simplest form, it consists of a tube with an opening at the end. The small hole in the end is positioned such that it faces the flowing fluid. The velocity of the fluid at the opening of the tube decreases to zero. This provides for the high pressure input to a differential pressure detector. A pressure tap provides the low pressure input.

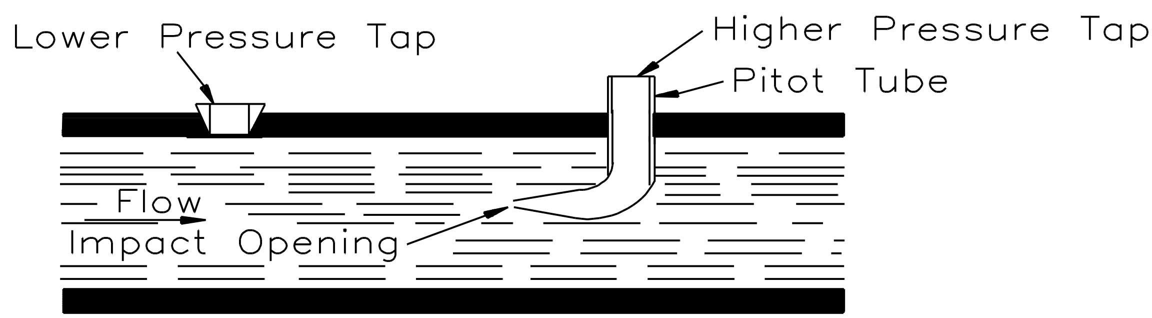

Figure 5 Pitot Tube

The pitot tube actually measures fluid velocity instead of fluid flow rate. However, volumetric flow rate can be obtained using Equation 4-4.

$$\dot{V} = KAV \tag{4-4}$$

where

$\dot{V}$ = volumetric flow rate (ft^3/sec.)
A = area of flow cross-section (ft^2)
V = velocity of flowing fluid (ft/sec.)
K = flow coefficient (normally about 0.8)

Pitot tubes must be calibrated for each specific application, as there is no standardization. This type of instrument can be used even when the fluid is not enclosed in a pipe or duct.

Summary

Head flow meters operate on the principle of placing a restriction in the line to cause a pressure drop. The differential pressure which is caused by the head is measured and converted to a flow measurement. The basic construction of various types of head flow detectors is summarized below.

Head Flow Meter Construction Summary

Orifice plates

- Flat plates 1/16 to 1/4 in. thick
- Mounted between a pair of flanges
- Installed in a straight run of smooth pipe to avoid disturbance of flow patterns due to fittings and valves

Venturi tube

- Converging conical inlet, a cylindrical throat, and a diverging recovery cone
- No projections into the fluid, no sharp corners, and no sudden changes in contour

Dall flow tube

- Consists of a short, straight inlet section followed by an abrupt decrease in the inside diameter of the tube
- Inlet shoulder followed by the converging inlet cone and a diverging exit cone
- Two cones separated by a slot or gap between the two cones

Pitot tube

- Consists of a tube with an opening at the end
- Small hole in the end positioned so that it faces the flowing fluid

OTHER FLOW METERS

Two other types of mechanical flow meters which can be used are the area flow and displacement meters. In addition, there exists much more sophisticated techniques for measurement of flow rate than use of differential pressure devices, such as anemometry, magnetic, and ultrasonic.

EO 1.3 DESCRIBE the following types of mechanical flow detectors, including the basic construction and theory of operation.

a. Rotameter
b. Nutating Disk

Area Flow Meter

The head causing the flow through an area meter is relatively constant such that the rate of flow is directly proportional to the metering area. The variation in area is produced by the rise and fall of a floating element. This type of flow meter must be mounted so that the floating element moves vertically and friction is minimal.

Rotameter

The rotameter, illustrated in Figure 6, is an area flow meter so named because a rotating float is the indicating element.

The rotameter consists of a metal float and a conical glass tube, constructed such that the diameter increases with height. When there is no fluid passing through the rotameter, the float rests at the bottom of the tube. As fluid enters the tube, the higher density of the float will cause the float to remain on the bottom. The space between the float and the tube allows for flow past the float. As flow increases in the tube, the pressure drop increases. When the pressure drop is sufficient, the float will rise to indicate the amount of flow. The higher the flow rate the greater the pressure drop. The higher the pressure drop the farther up the tube the float rises.

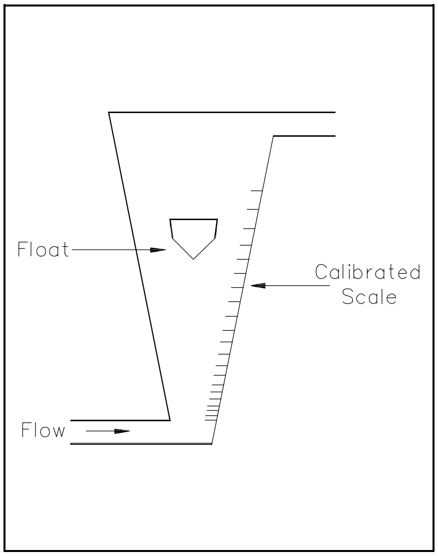

Figure 6 Rotameter

The float should stay at a constant position at a constant flow rate. With a smooth float, fluctuations appear even when flow is constant. By using a float with slanted slots cut in the head, the float maintains a constant position with respect to flow rate. This type of flow meter is usually used to measure low flow rates.

Displacement Meter

In a displacement flow meter, all of the fluid passes through the meter in almost completely isolated quantities. The number of these quantities is counted and indicated in terms of volume or weight units by a register.

Nutating Disk

The most common type of displacement flow meter is the nutating disk, or wobble plate meter. A typical nutating disk is shown in Figure 7.

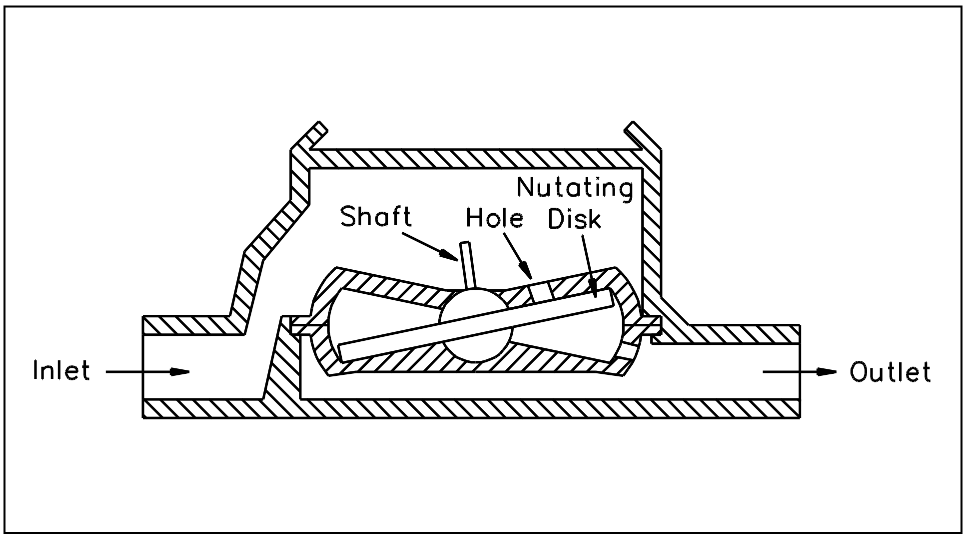

Figure 7 Nutating Disk

This type of flow meter is normally used for water service, such as raw water supply and evaporator feed. The movable element is a circular disk which is attached to a central ball. A shaft is fastened to the ball and held in an inclined position by a cam or roller. The disk is mounted in a chamber which has spherical side walls and conical top and bottom surfaces. The fluid enters an opening in the spherical wall on one side of the partition and leaves through the other side. As the fluid flows through the chamber, the disk wobbles, or executes a nutating motion. Since the volume of fluid required to make the disc complete one revolution is known, the total flow through a nutating disc can be calculated by multiplying the number of disc rotations by the known volume of fluid.

To measure this flow, the motion of the shaft generates a cone with the point, or apex, down. The top of the shaft operates a revolution counter, through a crank and set of gears, which is calibrated to indicate total system flow. A variety of accessories, such as automatic count resetting devices, can be added to the fundamental mechanism, which perform functions in addition to measuring the flow.

Hot-Wire Anemometer

The hot-wire anemometer, principally used in gas flow measurement, consists of an electrically heated, fine platinum wire which is immersed into the flow. As the fluid velocity increases, the rate of heat flow from the heated wire to the flow stream increases. Thus, a cooling effect on the wire electrode occurs, causing its electrical resistance to change. In a constant-current anemometer, the fluid velocity is determined from a measurement of the resulting change in wire resistance. In a constant-resistance anemometer, fluid velocity is determined from the current needed to maintain a constant wire temperature and, thus, the resistance constant.

Electromagnetic Flowmeter

The electromagnetic flowmeter is similar in principle to the generator. The rotor of the generator is replaced by a pipe placed between the poles of a magnet so that the flow of the fluid in the pipe is normal to the magnetic field. As the fluid flows through this magnetic field, an electromotive force is induced in it that will be mutually normal (perpendicular) to both the magnetic field and the motion of the fluid. This electromotive force may be measured with the aid of electrodes attached to the pipe and connected to a galvanometer or an equivalent. For a given magnetic field, the induced voltage will be proportional to the average velocity of the fluid. However, the fluid should have some degree of electrical conductivity.

Ultrasonic Flow Equipment

Devices such as ultrasonic flow equipment use the Doppler frequency shift of ultrasonic signals reflected from discontinuities in the fluid stream to obtain flow measurements. These discontinuities can be suspended solids, bubbles, or interfaces generated by turbulent eddies in the flow stream. The sensor is mounted on the outside of the pipe, and an ultrasonic beam from a piezoelectric crystal is transmitted through the pipe wall into the fluid at an angle to the flow stream. Signals reflected off flow disturbances are detected by a second piezoelectric crystal located in the same sensor. Transmitted and reflected signals are compared in an electrical circuit, and the corresponding frequency shift is proportional to the flow velocity.

Summary

The basic construction and theory of operation of rotameters, nutating disks, anemometers, electromagnetic flow meters, and ultrasonic flow equipment are summarized below.

Other Flow Meters Summary

Rotameter

- Consists of a metal float and a conical glass tube
- Tube diameter increases with height
- High density float will remain on the bottom of tube with no flow
- Space between the float and the tube allows for flow past the float
- As flow increases, the pressure drop increases, when the pressure drop is sufficient, the float rises to indicate the amount of flow

Nutating Disc

- Circular disk which is attached to a central ball
- A shaft is fastened to the ball and held in an inclined position by a cam, or roller
- Fluid enters an opening in the spherical wall on one side of the partition and leaves through the other side
- As the fluid flows through the chamber, the disk wobbles, or executes a nutating motion

Hot-Wire Anemometer

- Electrically heated, fine platinum wire immersed in flow
- Wire is cooled as flow is increased
- Measure either change in wire resistance or heating current to determine flow

Electromagnetic Flowmeter

- Magnetic field established around system pipe
- Electromotive force induced in fluid as it flows through magnetic field
- Electromotive force measured with electrodes and is proportional to flow rate

Ultrasonic Flow equipment

- Uses Doppler frequency shift of ultrasonic signals reflected off discontinuities in fluid

STEAM FLOW DETECTION

Steam flow detection is normally accomplished through the use of a steam flow nozzle.

EO 1.4 DESCRIBE density compensation of a steam flow instrument to include the reason density compensation is required and the parameters used.

The flow nozzle is commonly used for the measurement of steam flow and other high velocity fluid flow measurements where erosion may occur. It is capable of measuring approximately 60% higher flow rates than an orifice plate with the same diameter. This is due to the streamlined contour of the throat, which is a distinct advantage for the measurement of high velocity fluids. The flow nozzle requires less straight run piping than an orifice plate. However, the pressure drop is about the same for both. A typical flow nozzle is shown in Figure 8.

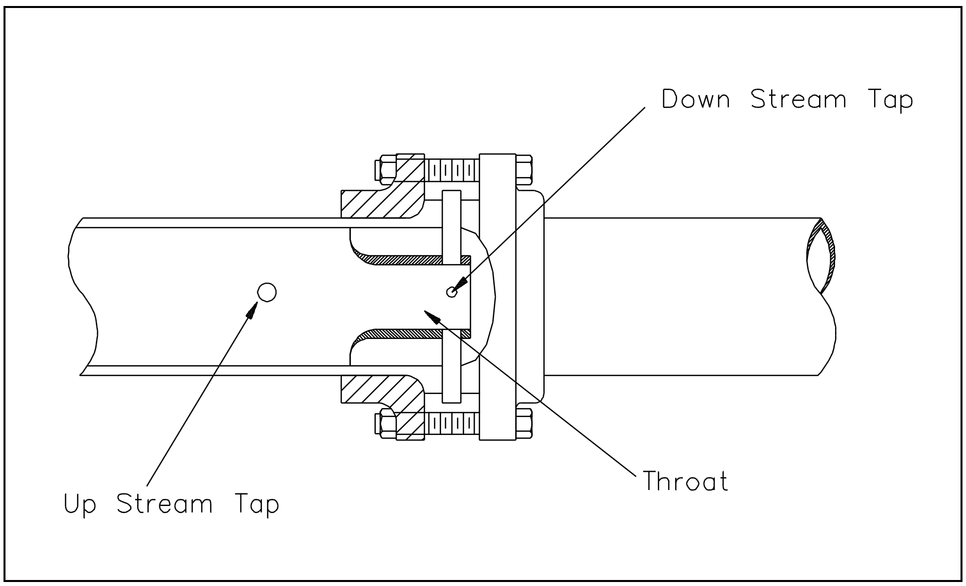

Figure 8 Flow Nozzle

Since steam is considered to be a gas, changes in pressure and temperature greatly affect its density. Equations 4-5 and 4-6 list the fundamental relationship for volumetric flow and mass flow.

$$\dot{V} = K\sqrt{\frac{\text{head loss}}{\rho}h} \tag{4-5}$$

and

$$\dot{m} = \dot{V}\rho \tag{4-6}$$

where

$\dot{V}$ = volumetric flow
K = constant relating to the ratio of pipe to orifice
h = differential pressure
ρ = density
$\dot{m}$ = mass flow

It is possible to substitute for density in the relationship using Equation 4-7.

$$\rho = \frac{pm}{R\theta} \tag{4-7}$$

where

ρ = density
p = upstream pressure
m = molecular weight of the gas
θ = absolute temperature
R = gas constant

By substituting for density, the values are used by the electronic circuit to calculate the density automatically. Since steam temperature is relatively constant in most steam systems, upstream pressure is the only variable in the above equation that changes as the system operates. If the other variables are hardwired, measuring the system pressure is all that is required for the electronics to calculate the fluid's density.

As the previous equations demonstrate, temperature and pressure values can be used to electronically compensate flow for changes in density. A simple mass flow detection system is illustrated by Figure 9 where measurements of temperature and pressure are made with commonly used instruments.

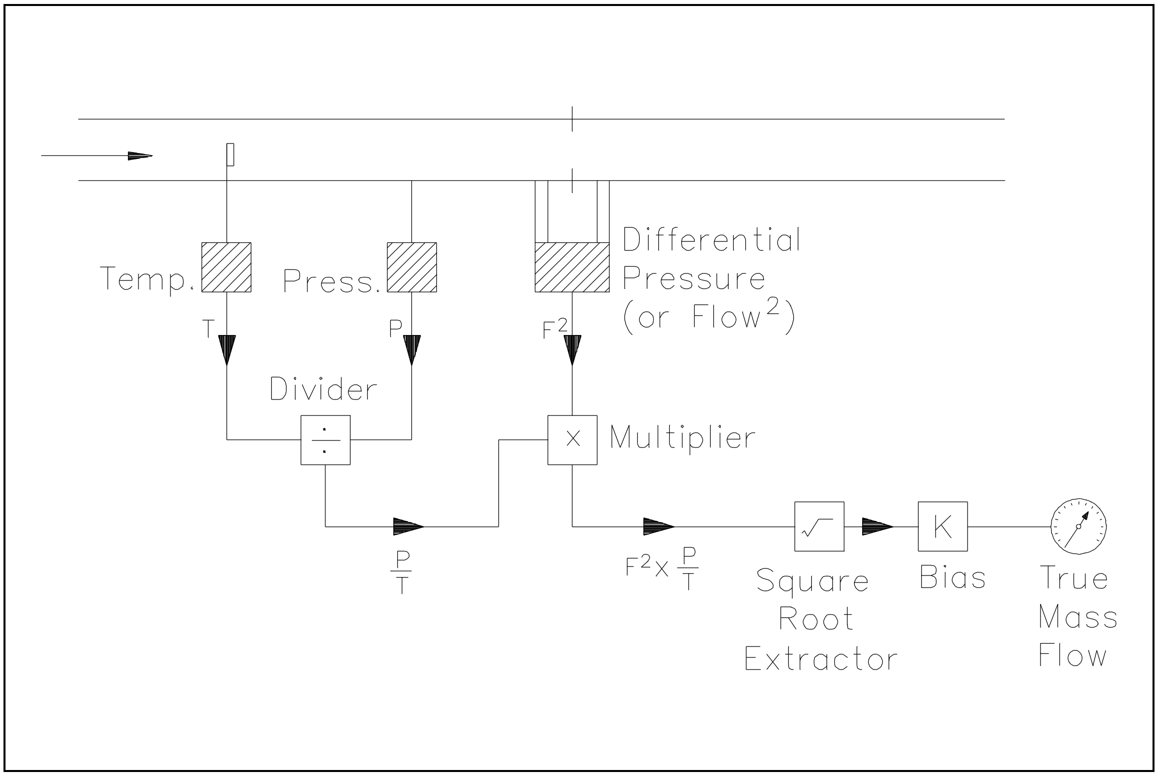

Figure 9 Simple Mass Flow Detection System

For the precise measurement of gas flow (steam) at varying pressures and temperatures, it is necessary to determine the density, which is pressure and temperature dependent, and from this value to calculate the actual flow. The use of a computer is essential to measure flow with changing pressure or temperature. Figure 10 illustrates an example of a computer specifically designed for the measurement of gas flow. The computer is designed to accept input signals from commonly used differential pressure detectors, or from density or pressure plus temperature sensors, and to provide an output which is proportional to the actual rate of flow. The computer has an accuracy better than $\pm$0.1% at flow rates of 10% to 100%.

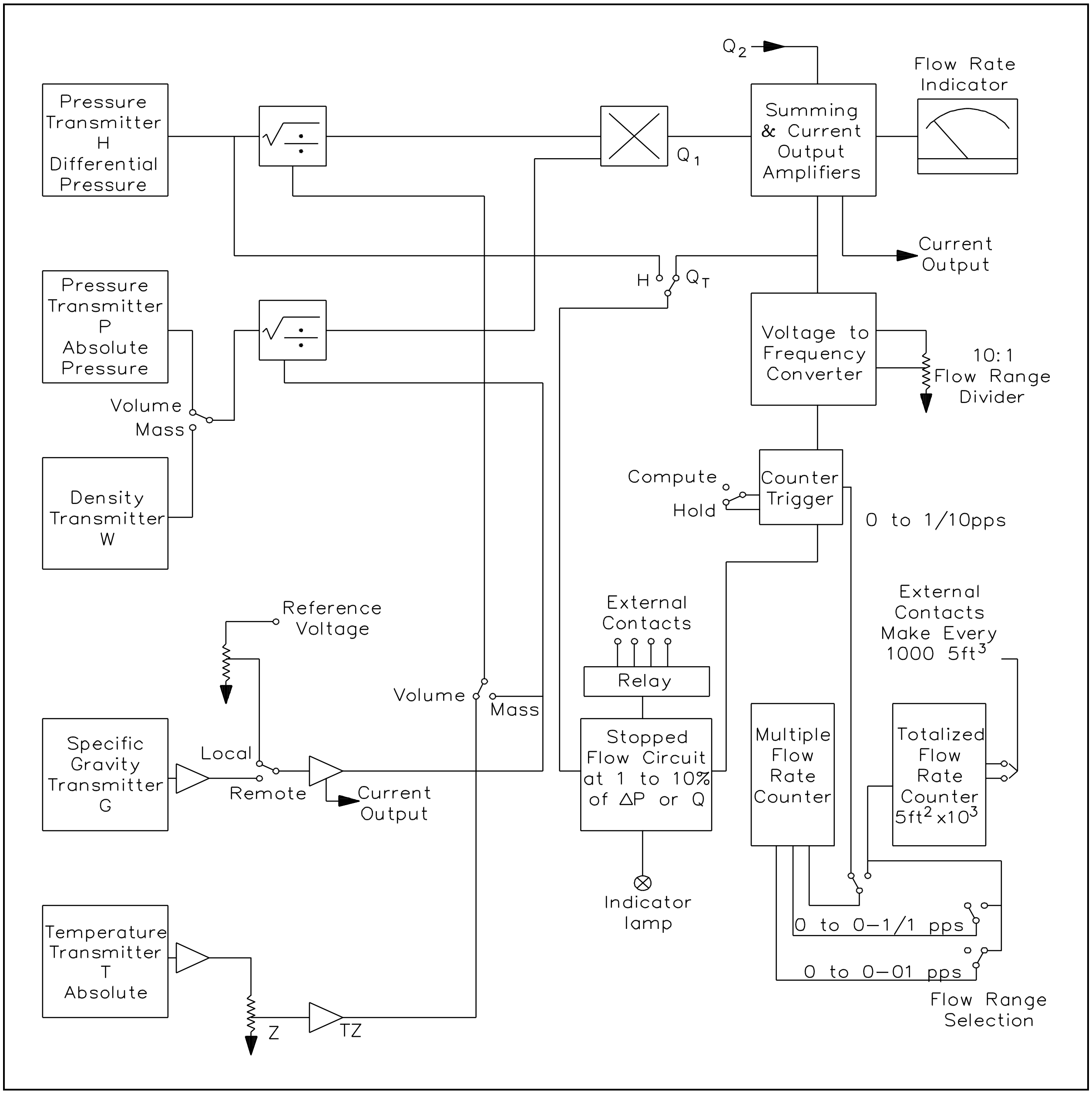

Figure 10 Gas Flow Computer

Summary

Density compensation is summarized below.

Density Compensation Summary

- Changes in temperature and pressure greatly affect indicated steam flow.
- By measuring temperature and pressure, a computerized system can be used to electronically compensate a steam or gas flow indication for changes in fluid density.

FLOW CIRCUITRY

The primary elements provide the input to the secondary element which provides for indications, alarms, and controls.

EO 1.5 Given a block diagram of a typical flow detection device, STATE the purpose of the following blocks:
- **a. Differential pressure (DP) transmitter**
- **b. Extractor**
- **c. Indicator**

EO 1.6 STATE the three environmental concerns which can affect the accuracy and reliability of flow sensing instrumentation.

Circuitry

Figure 11 shows a block diagram of a typical differential pressure flow detection circuit. The DP transmitter operation is dependent on the pressure difference across an orifice, venturi, or flow tube. This differential pressure is used to position a mechanical device such as a bellows. The bellows acts against spring pressure to reposition the core of a differential transformer. The transformer's output voltage on each of two secondary windings varies with a change in flow.

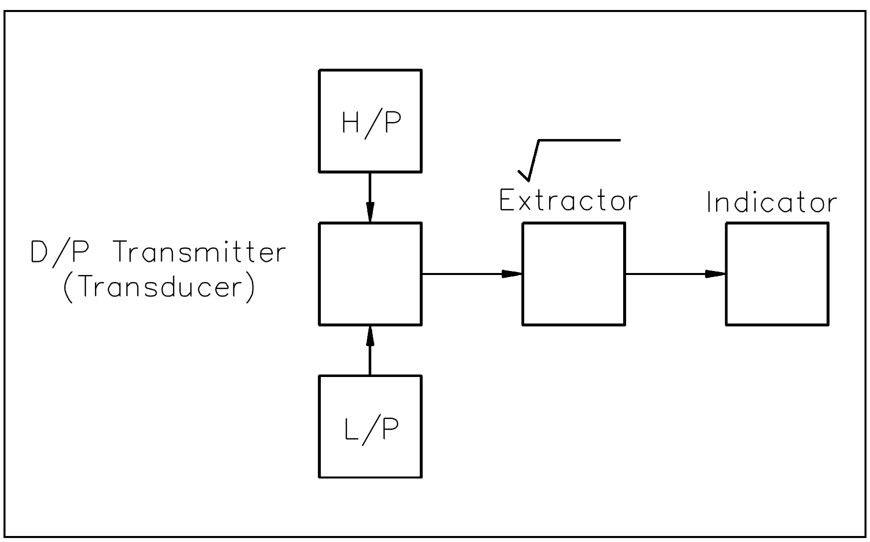

Figure 11 Differential Pressure Flow Detection Block Diagram

A loss of differential pressure integrity of the secondary element, the DP transmitter, will introduce an error into the indicated flow. This loss of integrity implies an impaired or degraded pressure boundary between the high-pressure and low-pressure sides of the transmitter. A loss of differential pressure boundary is caused by anything that results in the high- and low-pressure sides of the DP transmitter being allowed to equalize pressure.

As previously discussed, flow rate is proportional to the square root of the differential pressure. The extractor is used to electronically calculate the square root of the differential pressure and provide an output proportional to system flow. The constants are determined by selection of the appropriate electronic components.

The extractor output is amplified and sent to an indicator. The indicator provides either a local or a remote indication of system flow.

Use of Flow Indication

The flow of liquids and gases carries energy through the piping system. In many situations, it is very important to know whether there is flow and the rate at which the flow is occurring. An example of flow that is important to a facility operator is equipment cooling flow. The flow of coolant is essential in removing the heat generated by the system, thereby preventing damage to the equipment. Typically, flow indication is used in protection systems and control systems that help maintain system temperature.

Another method of determining system coolant flow is by using pump differential pressure. If all means of flow indication are lost, flow can be approximated using pump differential pressure. Pump differential pressure is proportional to the square of pump flow.

Environmental Concerns

As previously discussed, the density of the fluid whose flow is to be measured can have a large effect on flow sensing instrumentation. The effect of density is most important when the flow sensing instrumentation is measuring gas flows, such as steam. Since the density of a gas is directly affected by temperature and pressure, any changes in either of these parameters will have a direct effect on the measured flow. Therefore, any changes in fluid temperature or pressure must be compensated for to achieve an accurate measurement of flow.

Ambient temperature variations will affect the accuracy and reliability of flow sensing instrumentation. Variations in ambient temperature can directly affect the resistance of components in the instrumentation circuitry, and, therefore, affect the calibration of electric/electronic equipment. The effects of temperature variations are reduced by the design of the circuitry and by maintaining the flow sensing instrumentation in the proper environment.

The presence of humidity will also affect most electrical equipment, especially electronic equipment. High humidity causes moisture to collect on the equipment. This moisture can cause short circuits, grounds, and corrosion, which, in turn, may damage components. The effects due to humidity are controlled by maintaining the equipment in the proper environment.

Summary

The density of the fluid, ambient temperature, and humidity are the three factors which can affect the accuracy and reliability of flow sensing instrumentation. The purpose of each block of a typical differential pressure flow detection circuit is summarized below.

Flow Circuitry Summary

- The differential pressure is used by the DP transmitter to provide an output proportional to the flow.
- The extractor is used to electronically calculate the square root of the differential pressure and to provide an output proportional to system flow.
- The indicator provides either a local or a remote indication of system flow.

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